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Radiation Belt Test Model

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Final Report

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This Technical Report has been reviewed and is approved for publication.

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13. ABSTRACT *(Maximum 200 words)*

Rice University has developed a dynamic model of the Earth's radiation belts based on real-time data driven boundary conditions and full adiabaticity. The Radiation Belt Test Model (RBTM) successfully replicates the major features of storm-time behavior of energetic electrons: sudden commencement induced main phase dropout and recovery phase enhancement. It is the only known model to accomplish the latter.

The RBTM shows the extent to which new energetic electrons introduced to the magnetosphere near the geostationary orbit drift inward due to relaxation of the magnetic field. It also shows the effects of substorm related rapid motion of magnetotail field lines for which the 3rd adiabatic invariant is violated. The radial extent of this violation is seen to be sharply delineated to a region outside of 5Re, although this distance is determined by the Hilmer-Voigt magnetic field model used by the RBTM.

The RBTM appears to provide an excellent platform on which to build parameterized refinements to compensate for unknown acceleration processes inside 5Re where adiabaticity is seen to hold. Moreover, built within the framework of the MSFM, it offers the prospect of an operational forecast model for MeV electrons.

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1. Premise and Objectives of the Contract

1.1 Premise

The premise of the contract was that all adiabatic behavior of energetic electrons must be examined in a fully realistic, time-variable magnetic field before the effects of other acceleration or radial drift processes can be fully determined. Once adiabatic effects are modeled and understood the amount of additional drift or acceleration required can be obtained and added by submodels or parameterization. A corollary is that non-adiabatic effects can be detected by comparing the adiabatic model with satellite observations. Non-adiabatic effects may be treated locally (space and time-wise) by particle tracing or by parameterization.

1.2 Objectives

Based on the above premise, the objectives of the contract were to 1.) develop an energetic electron radiation belt test model, RBTM, based on the fully adiabatic formalism developed by Kim and Chan [1997]; 2.) test the model against satellite data and then; 3.) refine the model for improved performance by adding new drift algorithms or parameterizations that would correct shortcomings turned up in the testing process. The original plan was for phase 2, the testing, to be performed by the Air Force Research Laboratory. The last two phases could be repeated until satisfactory performance was achieved. Rice would develop the initial model and perform the refinement parameterization.

2. The RBTM

2.1 Basics of the model

The basic engine of the RBTM is the fully adiabatic model of Kim and Chan [1997]. This model assumes the conservation of all three adiabatic invariants, which amounts to the assumption that changes in the magnetic field along a particle path occur on a time scale that is long compared to the characteristic time scale of each of the three invariants. The most sensitive of these is the third invariant for which the longitudinal drift time for a 1 MeV electron at GEO is about 15 minutes. The model is specialized to the case of equatorially mirroring particles so that the second invariant is assumed to be zero. Using Liouville's theorem Kim and Chan show that the new equatorial flux j, (electrons/unit area, time, solid angle and energy) from time 1 to time 2 is

$$j(E_2, L_2; t_2) = \frac{B_2(L_2)}{B_1(L_1)} j(E_1, L_1; t_1) \tag{1}$$

where the E is the kinetic energy, L is the drift shell and $B_1(L_1)$ and $B_2(L_2)$ are the magnetic field strengths on the respective drift shells before and after the step.

The new drift shells are located numerically by integrating the polar flux around a contour of constant B until a drift path that conserves the flux enclosed by that L drift shell has been found. That sets the new B for the determination of the flux according to equation (1).

The new energy E_2 is determined using conservation of the (relativistically correct) first adiabatic invariant:

$$E_2 = -mc^2 + \sqrt{\frac{B_2(L_2)}{B_1(L_1)}(E_1^2 - 2mc^2 E_1) + (mc^2)^2} \tag{2}$$

The actual computational logic flow of the RBTM employs the following steps:

1. Setup: For a given drift shell L_n, calculate the enclosed ionospheric polar flux using Roederer's expression $\Phi_n = 2\pi a^2 B_o/L_n$, where a is the radius of the Earth, Roederer [1970];

2. Find a starting equatorial B_{test} for the same L_n using the dipole expression $B_{test}=B_o/L_n^3$;

3. For each local time grid point (j) find the colatitude for B_{test} using the Hilmer-Voigt model;

4. Find the polar flux Φ_{test} that is enclosed by these colatitude points using $\Phi_{test} = \Sigma_j\, 2\pi\, a^2 B_o \sin^2$ (colat (i,j)) / 48;

5. Compare Φ_n and Φ_{test}. If absolute difference > 0.01 then iterate using a new B_{test} until satisfied; (The new B is found by a bounded search.)

6. Compute new flux and energies at each grid point using the Kim and Chan flux and energy advancement equations shown above;

7. Average the computed fluxes over the drift shell and interpolate to the grid points.

2.2 Installation within the MSM

Early in the contract it was decided to install the RBTM as an new module within the Magnetospheric Specification Model, MSM/MSFM. This approach offered several advantages. It would provide the RBTM access to the Hilmer-Voigt magnetic field model within the MSM. It would provide access to all necessary input parameters. It would allow the use of the MSM graphic output for the energetic electrons, and finally it would permit easy transition to operation since the computer interface of the RBTM would be unchanged from that of the MSM. In fact, the original MSM lower energy electron and ion species output would still be available. The range of applicability of the MSM would be extended to 5 MeV electrons.

2.3 Boundaries and support parameters

The fully adiabatic model is a bounded, gridded model that requires initial electron fluxes at all grid points at the time of a cold start and dynamic input fluxes at the inner and outer boundaries. It was clear that the CRRESELE statistical model could be used to provide the starting electron fluxes. CRRESELE could also be used for the dynamic fluxes on the inner boundary at 2.5 Re provided the time resolution of CRRESELE, one day, could be improved to match the cadence of MSM with its 15 minute time-step.

The outer boundary presented a more difficult challenge because of known local-time variations in the energetic electron flux. CRRESELE is symmetric in local time and could not provide the required local-time dependent fluxes. Local-time variations were deemed to be less important at the

The outer boundary presented a more difficult challenge because of known local-time variations in the energetic electron flux. CRRESELE is symmetric in local time and could not provide the required local-time dependent fluxes. Local-time variations were deemed to be less important at the inner boundary. However, Rice had experience with artificial neural network systems that could be trained to provide the continuous dynamic fluxes on a model outer boundary set at the geostationary orbit. The neural network could be driven by solar wind data only. Moreover, if those data were obtained from an L1 spacecraft the Model would have intrinsic forecast capability.

The modeling region is the magnetic equatorial plane. Figure 1 shows the basic concept of the RBTM with the modeling region and the initial and boundary conditions specified.

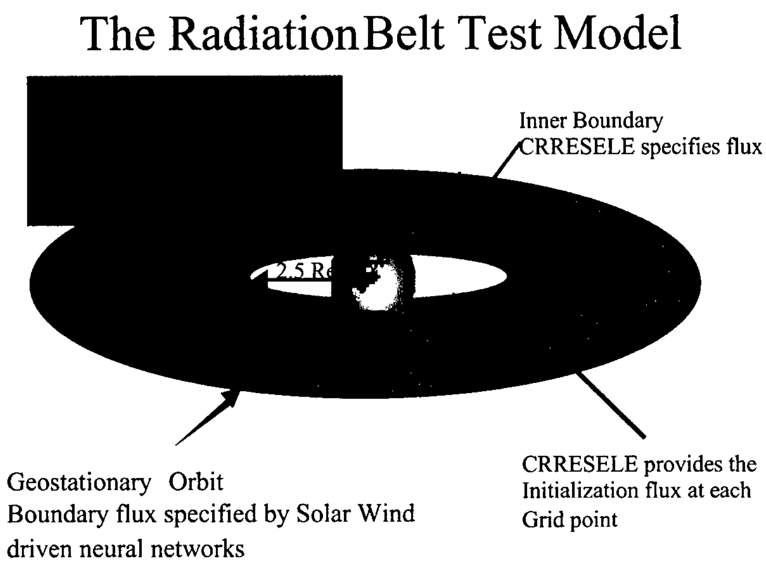


Figure 1. Modeling region and initial and boundary conditions for the RBTM

Figure 2 is a flow chart showing the modules of the revised MS(F)M as envisioned for the final product. Solar wind data, preferably from an L1 spacecraft is fed into the data conditioning routines within the MSM and into KPNET. KPNET is used to generate a pseudo Kp at 15-minute intervals. This is converted to Ap15 which is then used to generate a pseudo Ap15 at 15-minute intervals in time synchronism with the MSM time steps. CRRESELE can then provide the starting and inner boundary fluxes to the Fully Adiabatic Model (FAM). Meanwhile MSM is providing B-field values to FAM at the same cadence and the neural network using data from MSM can provided the outer boundary electron fluxes. (Note: in the delivered version this function is replaced by an interpolation of GEO satellite data.) The FAM computed fluxes are available for output in the MSM graphic display system.

An operator switch (not shown in Figure 2) permits the electron flux output to default to the pure CRRESELE output, thus providing a 15-minute CRRESELE update.

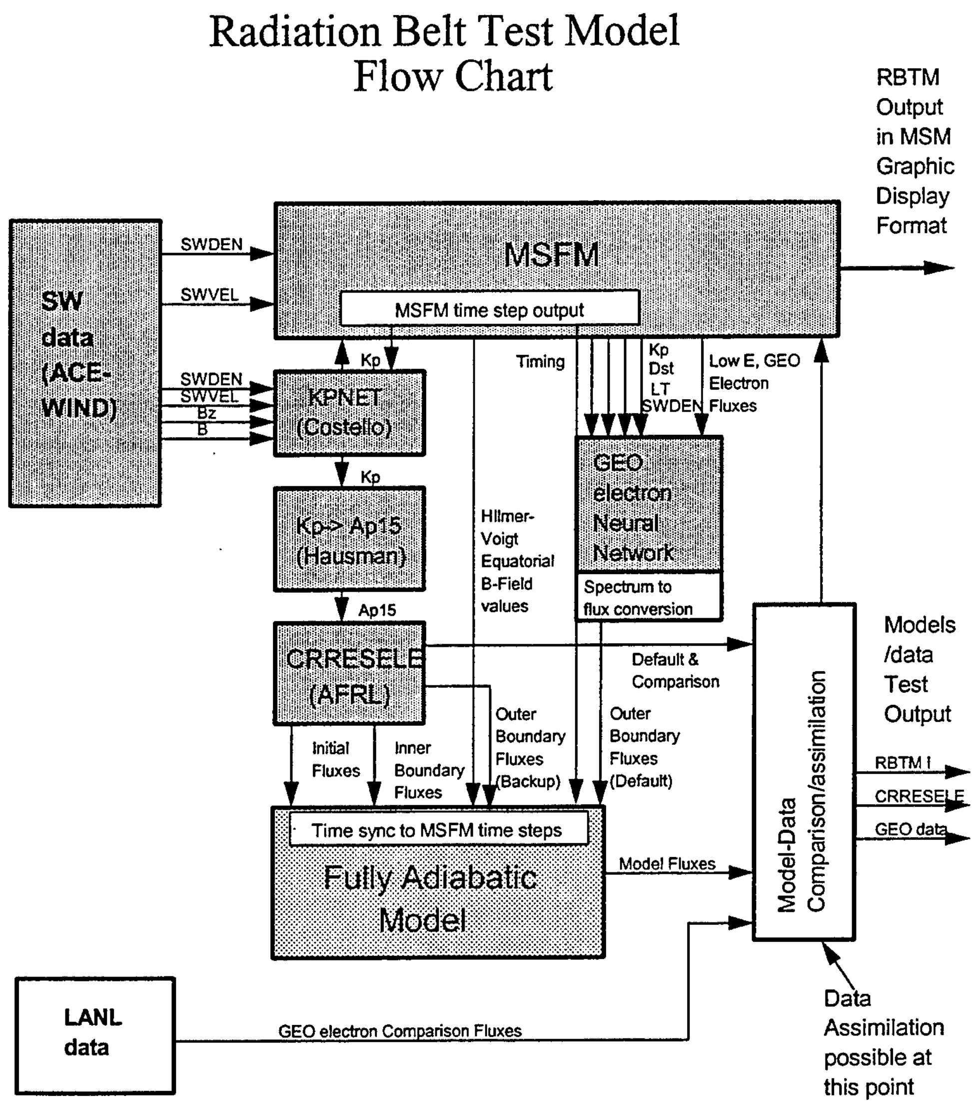


Figure 2. Flow chart for the RBTM.

2.4 The outer boundary flux specification

The proposed plan was to use an improved version of a neural network specification algorithm produced under a separate contract by O'Brien and Freeman [1998] to specify energetic electron fluxes on the outer boundary (6.6 Re). Upon examination it was determined that several errors that could affect the accuracy had been made in the preparation of that algorithm and that the neurons should be retrained. Work was begun on this during the summer of 1999 by an undergraduate intern Cadence Ellington. Most of the summer effort involved setting up the training data sets, which had to be rebuilt from scratch. As a result the retraining was not completed during the summer. It had been intended to finish that job during the summer of 2000. In the meantime, coding was completed by Bonnie Hausman on the rest of the model including the neural network to compute the 15-minute Ap15 to drive CRRESELE. Since the GEO electron neural network was not ready, and an outer boundary energetic electron specification was needed, it was decided to proceed in two intermediate steps. First we used CRRESELE as the outer boundary specification. This did not provide local time variation in the electron flux but it did allow us to begin an initial debugging of the code.

Next we prepared a GEO orbit electron flux specification for the November 3-8, 1993 magnetospheric storm using a two-dimensional interpolation of data from the LANL satellite 1990-046. The interpolation spread the data in local time and universal time using the MATLAB function GRIDDATA. This provided a useful dynamic test input data set for the GEO electron flux with the required local time, including diurnal, variation. This flux distribution is shown in Figure 3.

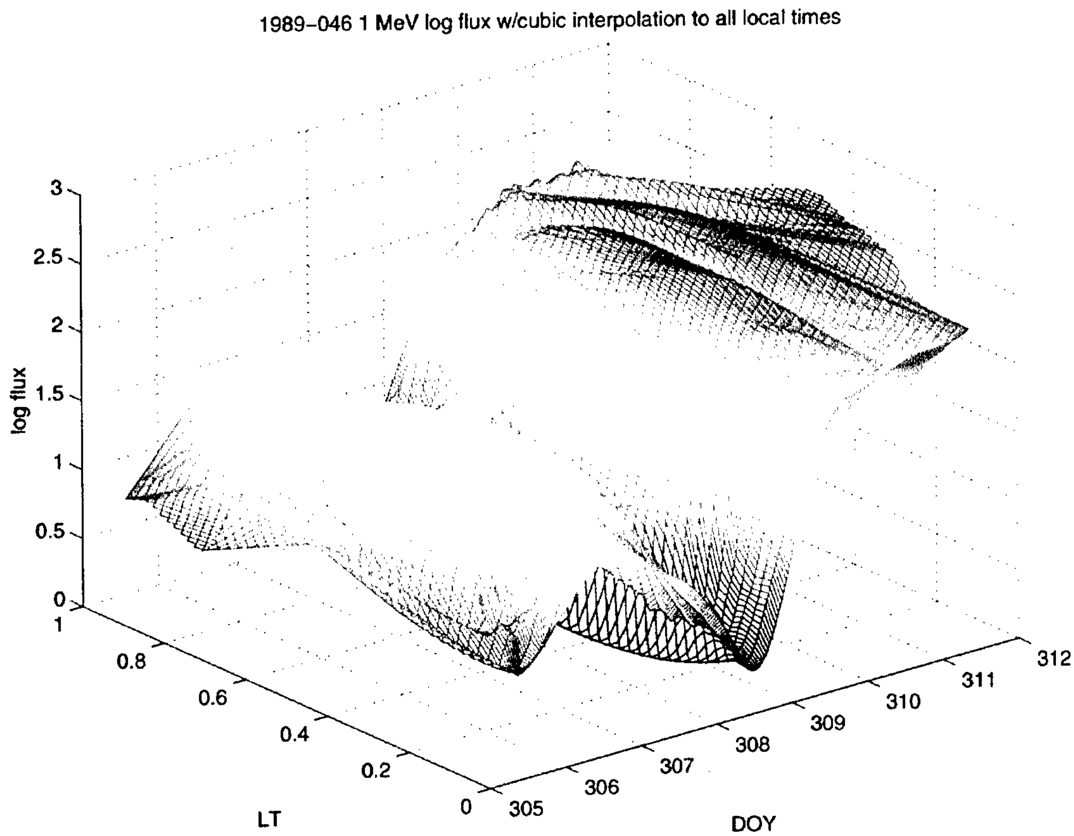


Figure 3. Plot of the 1 MeV electron data from satellite 1989–046 interpolated in Universal Time and Local Time as used as input for the outer boundary dynamic flux specification in the RBTM.

2.5 Preliminary Test Results

Because it is built as a module within the MSFM, the RBTM uses the MSM output graphics as the primary display mode. The only change from the standard MSM display was to cut off the outer boundary of the plotted energetic electron flux 2 Re beyond GEO. The displayed fluxes between GEO and the display boundary are obtained by an extrapolation.

Figure 4 is an example of the output plot from the November 1993 storm run. The circle just inside the model outer boundary represents the geostationary orbit. The Dst curve for the storm is also shown.

Exhaustive testing of the RBTM against satellite data was intended to be done by AFRL and is therefore outside the scope of the contract, however, we have conducted some limited tests using the November 1993 storm.

Figure 5 shows a sequence of frames throughout this storm for 1.6 MeV electrons as modeled by the RBTM. The frame letters refer to the times shown in the Dst curve in Figure 4. Following two prestorm frames, A and B, the compression from the sudden commencement can be seen in frame C. Frames D and E show the typical depletion at GEO associated with the main phase of the storm. The effects of a substorm can be seen in frames D and E. Dipolarization of the tail field reduces the flux at GEO substantially. This flux returns as the tail field expands outward again as seen in frame F. Frames G and H show the typical recovery phase enhancement. Note that the outer region fluxes exceed prestorm values.

In these runs the electron fluxes have been averaged around a drift-shell at the end of each time step thus washing out all local time variations except those due to the asymmetry of the magnetic field. This was done to maintain consistency with the full adiabatic concept of the model. However, RBTM test runs not incorporating the final drift-shell average show significant local time variations due to rapid field line motion in the tail. This field line motion occurs between 15-minute time steps of the model and on a time scale of the order of the electron longitudinal drift time thus resulting in a violation of the 3rd invariant which shows up in these (instructive) non-average runs. The delivered version of the RBTM has the final drift-shell average.

To summarize, these preliminary test runs indicate that the model is functioning as intended at this stage.

Based on the foregoing and additional inspection of the model output compared with the magnetic field model, we can make the following statements regarding the function of the RBTM:

1. The model replicates the main phase dropout.

2. There are strong perturbations of the magnetic field in the midnight region just outside of about 5 Re during the main phase/substorm period that break the 3rd adiabatic invariant of the MeV electrons.

3. The model reacts to these perturbations appropriately by pushing the electrons inward upon compression and pulling them outward during expansions, however, adiabaticity cannot be trusted at these times. A more elaborate particle tracing scheme is needed.

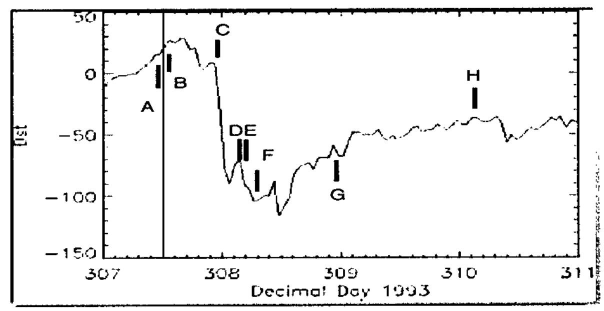
4. There is a relatively sharp inner boundary to these excursions of the field that lies just inside the geostationary orbit; fluxes are far more stable inside this boundary.

5. Inside 5Re, throughout the storm, adiabaticity probably works as a baseline but parameterization may be required for supplemental acceleration.

6. During the recovery phase electrons injected at GEO propagate inward to fill the region into at least 5 Re. This provides some recovery phase enhancement in the region.

7. A careful comparison with satellite data is needed.

8. A phase space density analysis would be useful.



The November, 1993 Storm Dst

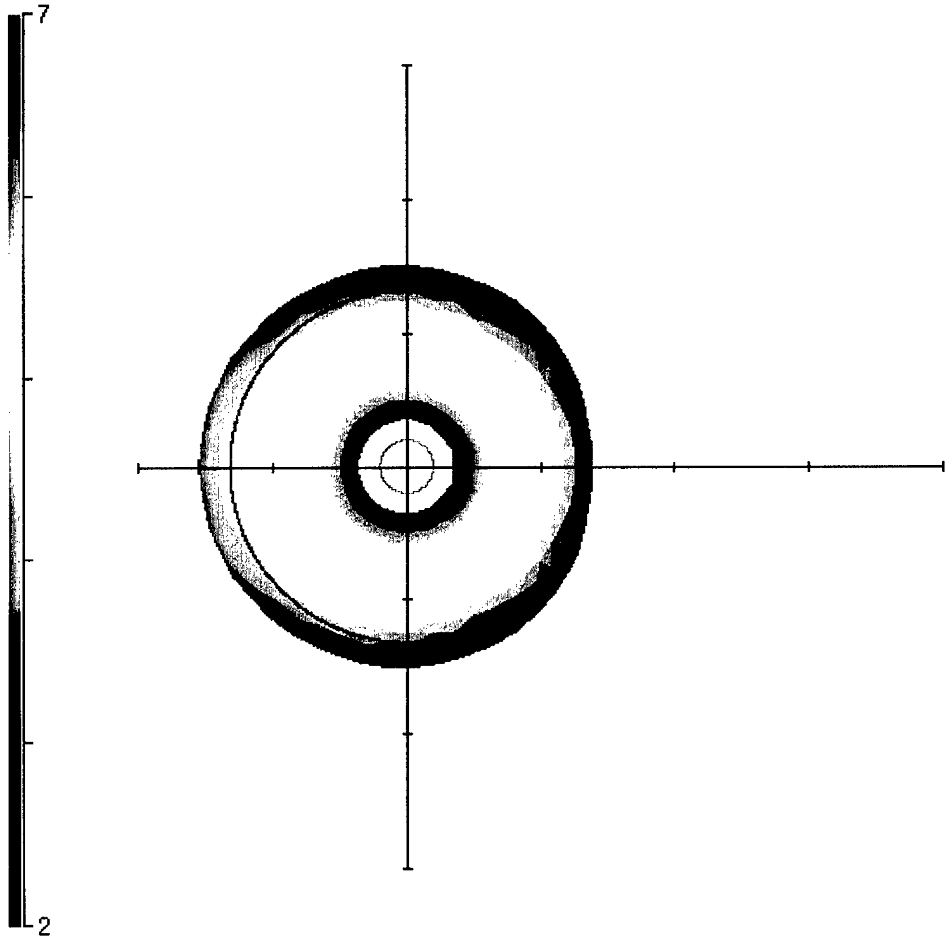


Figure 4. A single frame example of an output plot for the log flux of 1.6 MeV electrons for 09:15 UT, November 4, 1993. The Sun is on the left and the tic marks are 5 Re. The circle is the geostationary orbit. The color bar is the log flux in electrons/cm^2 s sr keV. This frame occurs just after a substantial expansion of the tail field following a substorm. The Dst plot is also shown.

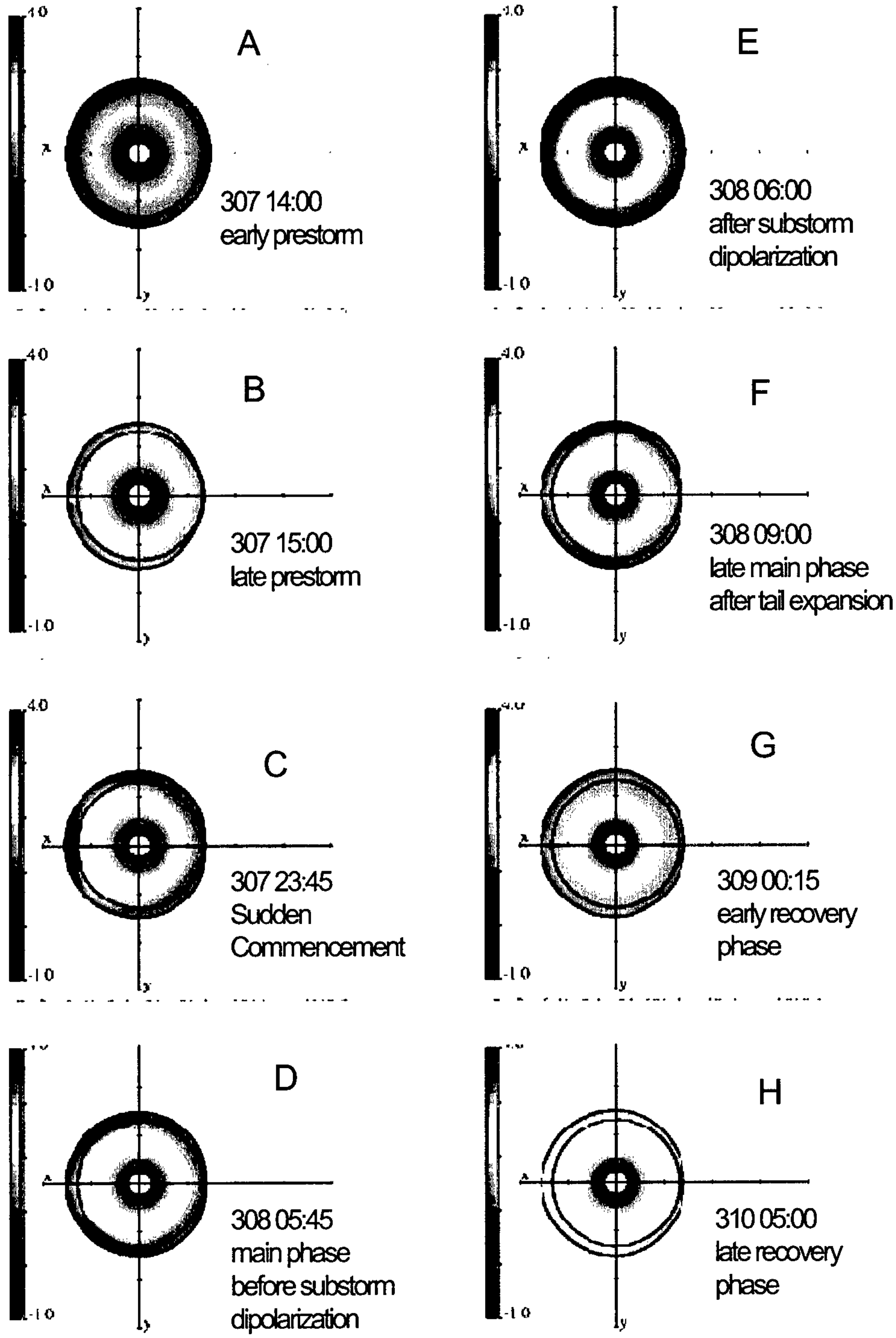


Figure 5. Sample output plots of the RBTM with the data shown in Figure 3. used as input for the outer boundary.

3. Delivered product

The delivered model is configured to run operationally using geostationary satellite data. These data are interpolated in local time and universal time to provide the real-time, dynamic outer boundary conditions to run the model. This mode is untested due to lack of time.

The model will have two output modes:

- Standard mode in which the output will be the RBTM computed electron fluxes
- CRRESELE output in which the fast CRRESELE fluxes replace the standard output. This mode is operator-selectable by coding the ENCHAN file to zero energy channels.

The delivered model uses the MSFM interface and requires only solar wind and LANL data to operate.

4. Summary and Recommendations

4.1 Summary

The RBTM runs and provides a useful dynamic simulation of energetic electrons in the equatorial plane of the Earth's magnetosphere. The RBTM has not been tested against satellite data and certainly needs additional algorithms to fine-tune the flux values and energies for greater fidelity. The limited testing that has been done using the November 1993 storm suggests the following observations:

1. Rapid storm/substorm field line motion beyond about 5 Re breaks the 3rd adiabatic invariant during certain times. Development of supplemental algorithms to address this region at these times is a next logical step in the refinement of this code but is beyond the scope of this contract. Full particle tracing may be required for this region and for certain times, with a "smart" sensing algorithm to determine when the full trace should kick in.

2. Inside 5 Re the fully adiabatic model could form a baseline algorithm upon which to build with parameterized adjustments to the flux and energy. The Kim-Chan equations (1) and (2) provide a convenient framework for accomplishing this. Coefficients could be added to the ratio of B terms that represent the rate-of-change of the field. Again, this cannot be done under the present contract.

3. Without extensive comparison with satellite data inside geostationary orbit, it is not possible to determine how much radial motion of the drift shells is being provided by the storm-time motion of field lines and therefore how much radial diffusion would need to be added to the model. Preliminary inspections suggest that the region just inside geostationary orbit fills in quickly during the recovery phase when flux enhancements occur at GEO. However, this might be an artifact of the current version of the model which cannot be considered to be fully debugged.

4. The delivered version of the code takes averages of the flux around each newly computed drift shell. This is done to preserve the concept of full adiabaticity, however, test versions of the code that did not that take *L*-shell averages revealed interesting local-time asymmetries in the midnight region that reveal the violation of the flux invariant.

5. The concept of using dynamic satellite data at GEO as an outer boundary specification along with CRRESELE for the inner and initial specification appears to work very well. Adding a neural network specification for the outer boundary flux would free the model from 1 AU input data and convert the RBTM to a true forecast model.

6. In summary, the RBTM concepts have been shown to work and the approach has been justified.

4.2 Recommendations

We recommend that this model be brought to completion by implementation of the following steps:

1. Train neural networks to provide the geostationary outer boundary fluxes.

2. Test the model thoroughly against satellite data and determine areas where adiabaticity is broken and acceleration, loss processes and/or radial diffusion is/are needed.

3. Add parameterization or individual particle drift algorithms to overcome the shortcomings found.

4. Retest and adjust parameterizations for optimal accuracy.

5. Replace existing MSM with this upgrade in operations.

5. Documentation

The following pages describe the RBTM code. The MSFM is not discussed here since there exists a separate final report for MSFM delivered to the Air Force on February 26, 1994 under contract F19628-90-K-0012. The output and input formats have not changed. All previous programs and graphics routines developed for the MSFM will work with the RBTM.

RBTM Users Manual

Types of input files for RBTM:

1) static files required for run

2) data files required for run

3) data files optional for run

Standard input format for RBTM subroutine INDATA

Example

```
4.000 1993.000 2.333 -999 -999 -999 -999 -999
4.333 1993.000 2.666 -999 -999 -999 -999 -999
5.000 1993.000 2.999 -999 -999 -999 -999 -999
```

The 8-word record is as follows:

Word 1 = data value at t
Word 2 = year at t (4-digits)
Word 3 = decimal day at t
Word 4 = spacecraft geomagnetic latitude at t
Word 5 = spacecraft geomagnetic longitude at t
Word 6 = spacecraft altitude at t
Word 7 = magnetic local time at t
Word 8 = data error quality values at t

Word 4-8 have not been implemented in the RBTM and are set to -999. Data are expected in time increasing order.

The Kp values should be input such that the data becomes a step function. For example on day 2 of 1993.0, if Kp =1 for hours 0-3 and Kp = 2 for hours 3-6 the file should look like

```
1.000 1993.000 2.0000 -999 -999 -999 -999 -999
1.000 1993.000 2.1240 -999 -999 -999 -999 -999
2.000 1993.000 2.1250 -999 -999 -999 -999 -999
2.000 1993.000 2.2490 -999 -999 -999 -999 -999
```

The Dst values should be shifted to the middle of the hour. For example if Dst is -20.0 for hours 0-1 and Dst is -40.0 for hours 1-2 the file should look like

```
-20.000 1993.000 2.020833 -999 -999 -999 -999 -999
-40.000 1993.000 2.062500 -999 -999 -999 -999 -999
```

Static Files Required for Runs

File	Description
boxxxxxxx.dat	The magnetic field matrices needed for the model run
COORD	Values used to set up the coordinate system
DKTABLE	Loss lifetimes for computing ion loss by charge exchange
EFCOEF	Coefficients from Heppner-Maynard model which are input to the electric field model
HARDY	Coefficients used by the Hardy electron precipitation model
IONENG	Coefficients used as input for the ion precipitation model
IONNUM	Coefficients used as input for the ion precipitation model

Data Files Required for Runs

File	Description	Format
EBINS	Number and value ranges of precipitating particle fluxes to be computed	EBINS (see attached documentation)
ENCHAN	Input values for the number of energy channels, particle type and energy channels for the model to simulate	ENCHAN (see attached documentation)
IMFBX	Hourly averaged Bx component of the interplanetary magnetic field in GSM coordinates for use in the Kp neural network	INDATA
IMFBY	Hourly averaged By component of the interplanetary magnetic field in GSM coordinates for use in the Kp neural network	INDATA
IMFBZ	Hourly averaged Bz component of the interplanetary magnetic field in GSM coordinates for use in the Kp neural network	INDATA
SWVEL	Hourly averaged solar wind velocity values for use in the Kp neural network	INDATA

RBTMIN	Specify: 1. Start and stop times 2. Logical record number for restart 3. 80 character run identification 4. Sunspot number 5. Output file prefix 6. Print control variable 0 = no print 1 = print 7. Cross polar cap correction factor (set to 1.34 prior to DBASE4) 8. Kpmode 0 = full-up RBTM run using all available data 1 = use Kp to produce proxy inputs 9. Forecast mode variable 0 = do not forecast 1 = forecast	RBTMIN (see attached documentation)

EBINS Format

This file contains the number and value ranges in eV of precipitating particle fluxes to be computed within the RBTM.

Example

4	Number of precipitating particle bins (Maximum 4)
30.,100.	30 - 100 eV energy range
100.,5000.	100 eV - 5 keV energy range
5000.,15000.	5 keV - 15 keV energy range
15000.,9999999.	>15 keV energy

ENCHAN Format

Input file ENCHAN controls how many electron energy channels are calculated.

The particle type is:

1 for electrons

The energy channels are in eV with the energies in ascending order. If the energy is less than 0.65 MeV or greater and 5.75 MeV the energy is reset.

Example

3	Number of energy channels (Maximum 37)
1 700000.	Electrons with energy 0.7 MeV
1 1000000.	Electrons with energy 10 MeV
1 1500000.	Electrons with energy 15 MeV

The particle types are integer; the particle energies are floating point.

If the number of energy channels is set to 0, the following default energies are used:

10	
1 650000.	Electrons with energy 0.65 MeV
1 950000.	Electrons with energy 0.95 MeV
1 1600000.	Electrons with energy 1.6 Mev
1 2000000.	Electrons with energy 2.0 MeV
1 2350000.	Electrons with energy 2.35 MeV
1 2750000.	Electrons with energy 2.75 MeV
1 3150000.	Electrons with energy 3.15 MeV
1 3750000.	Electrons with energy 3.75 MeV
1 4550000.	Electrons with energy 4.55 MeV
1 5750000.	Electrons with energy 5.75 MeV

If the number of energy channels is set to 0, care should be taken with applications which rely on the ENCHAN channel to give the energy channels for the run.

RBTMIN Format

The RBTMIN file contains the input and output times and other control variables for a particular RBTM run

Example

1992 57 46800	Start year, start day, start time in seconds
1992 57 48600	End year, end day, end time in seconds
0	Beginning record number (0 signifies a new start)
'30 minute test run'	Up to 80 character run identification
50.0	Sunspot number (see below for more information)
'a'	Output file prefix
1	Diagnostic print control variable 0 = no print 1= print
1.00	Cross polar cap correction factor (set to 1.34 for SSIES data generated prior to DBASE4 which went online in July 1993)
0	Kpmode 0 = full-up RBTM run using all available data 1 = use Kp to produce proxy inputs
0	Forecast mode variable (see below for more information) 0 = do not forecast 1 = forecast

The sunspot number is the standard published sunspot number and is available from the National Oceanic and Atmospheric Administration's Solar Geophysical Data available from the National Geophysical Data Center in Boulder, Colorado (see example attached). It is also available at the Web page of the Space Environment Center in Boulder. For an event, the sunspot number can be averaged. If the sunspot number is unavailable, the value of 50.0 should be used as a default.

To forecast Dst 1 hour ahead the following parameters are required:

IMF Bx, By, Bz	from -3 hours to current time
Solar Wind Density	current time
Solar Wind Velocity	current time
Dst	from -2 hours to current time

To forecast the cross polar cap potential 30 minutes ahead the following parameters are required:

IMF Bx,By,Bz	from -2 hours to current time
Solar Wind Velocity	from -2 hours to current time

To forecast the equatorward edge of the auroral oval 1 hour ahead the following parameters are required:

IMF Bx,By,Bz	from -2 hours to current time

Solar Wind Velocity or cross-polar cap potential from -2 hours to current time

Data Files Optional for Run

File	Units	Description	Format
DST	Nanotesla	Dst values for the event	INDATA
EQEDGE	Degrees	Low latitude boundary of the auroral oval projected to midnight	INDATA
PCP	Kilovolts	Polar cap total potential drop for event used as input to the electric field model	INDATA
SUMKP	None	The sum of the 3-hour Kp index for each of the 10 days preceding the current day. These data are used by the high-energy electron subroutine.	INDATA
SWDEN	cm^{-3}	Solar wind density values used to calculate the standoff distance for the event	INDATA
XIPATT	None (see attached documentation)	Polar cap potential pattern used as input to electric field model for the event	INDATA

Output Files
Standard Output

File	Units	Description	Format
aloct	Radians eastward from noon	Grid local time array	2-d OUTPUT format
augpar	Various	Augmented data array for input values	1-d OUTPUT format
bmin	nT	Equatorial magnetic field strength	2-d OUTPUT format
bndloc	None	Location of outer boundary of detailed particle traces	1-d OUTPUT format
colat	Radians	Grid colatitude array	2-d OUTPUT format
eavg	eV	Average energy in precipitating energy bins for electrons	5-d OUTPUT format
flux	#/cm^2-s-keV	Flux values for all invariant energy channels at all grid points	3-d OUTPUT format
fluxke	eV	Flux values at constant kinetic energy at all grid points	3-d OUTPUT format
flxbnd	#/cm^2-s-eV-sr	Flux values at constant kinetic energy at all grid points	2-d OUTPUT format
flxsum	ergs/cm^2-s	Binned precipitating energy flux for electrons	5-d OUTPUT format
infofile	None	Information output from model run	Ascii text
ipiflx	eV	Average energy in precipitating energy bins for ions	5-d OUTPUT format
ipieng	ergs/cm^2-s	Binned precipitating energy flux for ions	5-d OUTPUT format
mode	None	Integer array containing information on the sources of the input data used	1-d OUTPUT format

v	Volts	Electric potential distribution on grid (average of vnrth and vsoth)	2-d OUTPUT format
vm	$(Re/nT)^{-2/3}$	(Flux tube volume)$^{-2/3}$	2-d OUTPUT format

File	Units	Description	Format
vnrth	Volts	Northern hemisphere electric potential distribution	2-d OUTPUT format
vsoth	Volts	Southern hemisphere electric potential distribution	2-d OUTPUT format
xmin	Re	GSM X location of where field line point through grid point crosses the equatorial (B-field minimum) plane	2-d OUTPUT format
ymin	Re	GSM Y location of where field line point through grid point crosses the equatorial (B-field minimum) plane	2-d OUTPUT format
zmin	Re	GSM Z location of where field line going through grid point crosses the equatorial (B-field minimum) plane	2-d OUTPUT format

Standard OUTPUT Interface

The standard call to subroutine OUTPUT is:

CALL OUTPUT(LUN, IRECMX, ID, RID, CHID, ARRAY, IDIM, JDIM, KDIM, IMAX, JMAX, KMAX, PREFIX, FILNAM)

LUN	Logical Unit number on which to write file
IRECMX	Record Number to begin write function
ID	Integer header vector
ID(1)	Year
ID(2)	Day
ID(3)	Hour
ID(4)	Minutes
ID(5)	Seconds
ID(6)	Presently unused
ID(7)	Presently unused
ID(8)	First dimension of output array
ID(9)	Second dimension of output array
ID(10)	Third dimension of output array
ID(11)	Time index L
ID(12-20)	Presently unused
RID	Real header vector
RID(1)	Time tag (seconds)
RID(2)	Kp
RID(3)	Polar cap potential drop (kV)
RID(4)	Time derivative of location of low-latitude edge of auroral oval (degrees/hour)
RID(5-20)	Presently unused
CHID	Character header string (up to 80 characters long) read in from RBTMIN.
ARRAY	Array to be written
IDIM	I dimension of array
JDIM	J dimension of array
KDIM	K dimension of array
IMAX	Actual I maximum in output ARRAY
JMAX	Actual J maximum in output ARRAY
KMAX	Actual K maximum in output ARRAY
PREFIX	Run identification character from RBTMIN
FILNAM	File to be written

1-d OUTPUT Format

These files are written by SUBROUTINE OUTPUT and have the same structure:

Record 1ID, RID, CHID, ARRAY for timestep 1
Record 2ID, RID, CHID, ARRAY for timestep 2

.

.

Record nID, RID, CHID, ARRAY for timestep n

For the following 1-d OUTPUT files the only parameter that changes is the record length because of the different ARRAY sizes:

augpar Dimension NAUGEL (currently set to 28)

The augpar array contains:

augpar(1)	Year
augpar(2)	Day
augpar(3)	Seconds of day
augpar(4)	Minute
augpar(5)	Seconds
augpar(6)	Kp
augpar(7)	Dst (nT)
augpar(8)	Equatorward edge of the auroral oval at midnight (degrees)
augpar(9-11)	Presently unused
augpar(12)	Bx component of the interplanetary magnetic field (nT)
augpar(13)	By component of the interplanetary magnetic field (nT)
augpar(14)	Bz component of the interplanetary magnetic field (nT)
augpar(15)	Magnetotail collapse parameter
augpar(16-20)	Presently unused
augpar(21)	Solar wind velocity (km/s)
augpar(22)	Solar wind density (cm^{-3})
augpar(23)	Presently unused
augpar(24)	Standoff distance
augpar(25)	Cross polar cap potential drop (kV)
augpar(26)	Electric field pattern type
augpar(27)	Time rate of change of Dst (nT/hour)
augpar(28)	Time rate of change of the equatorward edge of the auroral oval at midnight (degrees/hour)

bndloc Dimension JDIM (currently set to 51)
The bndloc array contains the floating point i value of the outer boundary of the particle traces for each local time (j) gridpoint.

mode Dimension NAUGEL (currently set to 28)

For each of the 28 augpar variables given above, the mode array contains information on where the input data was obtain from:

0 Default (Kp-based) front-end model used
1 Data from input data stream
2 Forecast module value used
3 Persistence value used
4 Interpolated value between forecast and data stream value
5 Interpolated value between data stream and default values
6 Interpolated between forecast and default values

2-d OUTPUT Format

These files are written by SUBROUTINE OUTPUT and have the same structure as the 1-d OUTPUT format:

Record 1ID, RID, CHID, ARRAY for timestep 1
Record 2ID, RID, CHID, ARRAY for timestep 2

.

.

Record nID, RID, CHID, ARRAY for timestep n

The ID, RID and CHID also have the same structure.

The following arrays are dimensioned IDIM (currently set to 62) by JDIM (currently set to 62)

- aloct
- bmin
- colat
- v
- vm
- vnrth
- vsoth
- xmin
- ymin
- zmin

The following array is dimensioned JDIM (currently set to 51) by KDIM (currently set to 37)

- flxbnd

3-d OUTPUT format

These files are written by SUBROUTINE OUTPUT and are used by the flux and fluxke output files. For k energy channels the format is:

Record 1ID, RID, CHID, ARRAY for energy 1 for timestep 1
Record 2ID, RID, CHID, ARRAY for energy 2 for timestep 1

.

.

Record kID, RID, CHID, ARRAY for energy k for timestep 1
Record k+1 ID, RID, CHID, ARRAY for energy 1 for timestep 2
Record k+2 ID, RID, CHID, ARRAY for energy 2 for timestep 2

.

.

Record k+n ID, RID, CHID, ARRAY for energy k for timestep n

The ID, RID and CHID also have the same structure.

The flux arrays are dimensioned IDIM (currently set to 62) by JDIM (currently set to 62) by KDIM (maximum 37)

5-d OUTPUT Format

These files are written by SUBROUTINE OUTPUT and are used by the precipitating number and average energy electron and ion output files. The number of bins is set in file EBINS, with the maximum number of 4

Record 1ID, RID, CHID, ARRAY for bin 1 for timestep 1
Record 2ID, RID, CHID, ARRAY for bin 2 for timestep 1
Record 3ID, RID, CHID, ARRAY for bin 3 for timestep 1
Record 4ID, RID, CHID, ARRAY for bin 4 for timestep 1
Record 5ID, RID, CHID, ARRAY for bin 1 for timestep 2

.

.

Record n+4 ID, RID, CHID, ARRAY for bin 4 for timestep n

The ID, RID and CHID also have the same structure.

The arrays are dimensioned IDIM (currently set to 62) by JDIM (currently set to 62) by KBNDIM (currently set to 4) by ITMDIM (currently set to 50)

The following files use this format:

flxsum
eavg
ipiflx
ipieng

APCAL

a. Function - Function to calculate Ap15 from neural net coefficients.

b. Input -

FKPIN Vector of Kp values for current time step to timestep 15 (3.5 hours)

c. Processing - Uses neural network coefficients to calculate Ap15.

d. Output -

APCAL Ap15 value for current time step

APNN

a. Function - Subroutine to calculate Ap15 from neural net coefficients.

b. Input -

ITMMAX Maximum number of time labels
NELTS Number of elements in output data array
ITMDIM Maximum number of time steps per run
NAUGEL Number of elements in the augmented input array
PREFIX Prefix for current run

c. Processing - following are the subroutines called and their major functions

APCAL Uses neural network coefficients to calculate Ap15.

This routine reads in the necessary input data for the Ap15 neural network and calls the function APCAL to calculate the Ap15 value for each timestep in the run. The neural network requires the current Kp and the Kp value for 15 previous time steps. If this is a new run, all values are set using the current Kp value. The calculated Ap15 value is put into PARRAY(20,itm).

d. Output -

PARRAY Data array of interpolated data values
MODE Integer variable denoting input data sources
0 Default (Kp-based) front-end model used
1 Data from input data stream
2 Forecast module value used
3 Persistence value used
4 Interpolated value between forecast and data stream value
5 Interpolated value between data stream and default values
6 Interpolated between forecast and default values

BNDCRS

a. Function - Set up boundary flux at 2.5 and 6.75 Re from CRRESELE model. Set up geosynchronous orbit flux at 6.6 Re.

b. Input -

LATDIM	Number of latitudinal grid lines
LTDIM	Number of local time grid lines
ITMDIM	Maximum number of times steps per run
ITMMAX	Maximum number of time labels
IEDIM	Maximum number of energy channels per run
IEMAX	Number of energy channels in current run
NAUGEL	Number of elements in the augmented input array
FLXCRS	Flux by energy and L shell from the CRRESELE model (electrons/cm^2-s-keV)
XKE	Energy channels used in current run (MeV)
AUGPAR	Augmented array of input values
R	RBTM grid in Re for current time step
COLAT	Grid colatitude array (radians)
LL	Number of current time step

c. Processing - the following are the subroutines called and their major functions:

FNDBI	Determines BI value corresponding to a given R for a specified J line
GEOFLX	Subroutine to read file of geosynchronous fluxes and place in RBTM grid. Reads file of geosynchronous flux and locates them in the RBTM grid.

d. Output -

FLXCRB	Flux at 2.5 Re in RBTM grid for all energies (electrons/cm^2-s-keV)
BNCREQ	I value of point at 2.5 Re
FLXPL	Flux at 6.75 Re in RBTM grid for all energies (electrons/cm^2-s-keV)
BNDPL	I value of point at 6.75 Re
FLXGEO	Flux at geosynchronous orbit for all local time for current time step for given energy (electrons/cm^2-s-keV)

GEOFLX

a. Function - Subroutine to read file of geosynchronous fluxes and place in RBTM grid.

b. Input -

LATDIM	Number of latitudinal grid lines
LTDIM	Number of local time grid lines
ITMDIM	Maximum number of time steps per run

IEDIM	Maximum number of energy channels per run
NAUGEL	Number of elements in the augmented input array
ITM	Current time step
IEMAX	Number of energy channels in current run
AUGPAR	Augmented data array for input values

c. Processing -
d. Output -

FLXGEO	Flux at geosynchronous orbit for all local time for current time step (electrons/cm^2-s-keV)

INTCRS

a. Function - Set up initial flux distribution using CRRESELE model.

b. Input -

LATDIM	Number of latitudinal grid lines
LTDIM	Number of local time grid lines
IEDIM	Maximum number of energy channels per run
IEMAX	Number of energy channels in current run
ITMDIM	Maximum number of times steps per run
R	RBTM grid in Re for current time step
XKE	Energy channels used in current run (MeV)
XMOD	Ap15 value for initial time step

c. Processing - Reads file of flux and L-shell data from CRESSELE model data files and places them onto RBTM grid.

d. Output -

FLXCRS	Flux values from CRRESELE model by energy by L-shell (electrons/cm^2-s-keV)
BIN	L values used in CRRESELE model.
FLXBEG	Initial flux values for each energy on RBTM grid (electrons/cm^2-s-keV)

KPNN

a. Function - Calculate Kp using neural network coefficients and enter into DARRY.

b. Input -

NDIM	Dimension of DARRY giving maximum number of data records
DARRY	Observational data array
NUMNUM	Number of observational data elements

ISTART Run start time (year,day,seconds)

c. Processing - The following are the subroutines called and their major functions

FORTIM Performs model time conversion
KPNNCON Kp calculation controller

If this is the 1st time step, the forecast Kp value is put in the T+1 hour position in DARRY and the T, T+15 minutes, T+30 minutes and T+45 minutes values are backfilled with the same Kp.

d. Output -

DARRY Observational data array with neural net Kp entered

KPNNCON

a. Function - Kp neural net controller

b. Input -

YEAR Year
FDAY Decimal day

c. Processing - Following are the subroutines called and their major function:

GETHIS Parameter history acquisition routine for the Kp neural net
KPNNMOD Kp neural network model

d. Output -

Kp Neural net calculated Kp
IERR Error return
=0 Forecast complete
=1 No forecast because of missing data

KPNNMOD

a. Function - Function to calculate Kp from neural net coefficients.

b. Input -

B IMF hourly average B-field magnitude for time T and time T-1 hour (nT)
By IMF hourly average of the Y-component for time T and time T-1 hour (nT)
Bz IMF hourly average of the Z-component for time T and time T-1 hour (nT)
SWVEL Solar wind speed hourly average for time T and T-1 hour (Km/s)

c. Processing - Uses neural network coefficients to calculate Kp.

d. Output -

FORVAL	Kp value for hour T+1
IERR	Error flag =1 Problem in data normalization (value is > 1 or < 0) the value is reset (to 0 or 1) and the neural network continues =2 Calculate Kp is < 0 or > 9

PARGEN

a. Function - Subroutine to obtain values from the environmental data base and interpolate or extrapolate as appropriate to provide data at a normalized time.

b. Input -

ISTART	Start time (year,day,seconds)
IINC	Increment time (year,day,seconds)
IEND	Stop time (year,day,seconds)
ITMDIM	Maximum number of times steps per run
NELTS	Number of elements in output data array
ITMMAX	Maximum number of time labels
TIMTAG	Vector giving times at which E and B parameters are calculated
NAUGEL	Number of elements in the augmented input array
XIP	Saved IPATT DARRY
XPCP	Saved PCP DARRY
NIP	Number of data elements in XIP
NPCP	Number of data elements in XPCP
PREFIX	Single character prefix for current run

c. Processing - The following are the subroutines called and their major functions:

APNN	Subroutine to calculate Ap15 from neural net coefficients
INDATA	Subroutine to read in data for the MSFM
DTACHK	Subroutine to check for input data values out of range
SMOOTH	Subroutine to extract data from input array
DTXIPT	Subroutine to return interpolated polar cap patterns
DTNTRP	Subroutine to return interpolated data values
TIMINC	Subroutine to increment time for next electric and magnetic field record
TCONV3	Function subprogram to convert to standard program representation of time.

This subroutine retrieves observational data from the environmental data base and interpolates as necessary to have input data form the entire run.

d. Output -

PARRAY	Data array of interpolated data values
MODE	Integer variable denoting input data sources
0	Default (Kp-based) front-end model used
1	Data from input data stream
2	Forecast module value used
3	Persistence value used
4	Interpolated value between forecast and data stream value
5	Interpolated value between data stream and default values
6	Interpolated between forecast and default values

RADBLT

a. Function - Calculate Radiation Belt electron flux using fully adiabatic method.

b. Input -

IEMAX	Number of energy channels in current run
C1	Grid colatitude array for previous time step (radians)
FLUX1	Flux by energy on RBTM grid for previous time step (electrons/cm^2-s/keV)
XKE	Energy channels used in current run (MeV)
FNDPL1	Flux at 6.75 Re in RBTM grid for all energies for previous time step (electrons/cm^2-s-keV)
BNDPL1	I value of point at 6.75 Re for previous time step
FBNDEQ1	Flux at 2.5 Re in RBTM grid for all energies for previous time step (electrons/cm^2-s-keV)
BNDEQ1	I value of point at 2.5 Re for previous time step
B1	Magnetic field magnitude at equatorial plane for previous time step (nT)
B2	Magnetic field magnitude at equatorial plane for current time step (nT)
C2	Grid colatitude array for current time step (radians)
FNDPL2	Flux at 6.75 Re in RBTM grid for all energies for current time step (electrons/cm^2-s-keV)
BNDPL2	I value of point at 6.75 Re for current time step
FBNDEQ2	Flux at 2.5 Re in RBTM grid for all energies for current time step (electrons/cm^2-s-keV)
BNDEQ2	I value of point at 2.5 Re for current time step
R	RBTM grid in Re for current time step
FLXGEO	Flux at geosynchronous orbit for all local time for current time step for given energy (electrons/cm^2-s-keV)

c. Processing - The following are the subroutines called and their major functions:

FLXCALC	Calculates energy and flux change on each L shell and places them onto RBTM grid

FRL	Function to calculate phi (3rd adiabatic invariant)
G3NTRP	Generic 3d interpolation function
SETUP	Calculates L shells and location from magnetic field of previous time step
SHLDFT	Calculates L shells and location from magnetic field of current time step
YFIT	Function to do linear interpolation

d. Output -

FLUX2	Flux by energy on RBTM grid for current time step (electrons/cm^2-s/keV)
BNDLOC	Outer boundary set at 8.0 Re

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